SPECKLE REDUCTION IN ULTRASONIC SAFT IMAGES IN COARSE GRAINED MATERIAL THROUGH SPLIT SPECTRUM PROCESSING

Yue Li, Vernon L. Newhouse, and P. M. Shankar
Biomedical engineering and Science Institute
Drexel University, Philadelphia, PA 19104

Prasanna Karpur
Nondestructive Evaluation Branch
AFWAL/MLLP, Department of the Air Force
Air Force Wright Aeronautical Laboratories,
Wright- Patterson Airforce Base, OH 45433-6533.

INTRODUCTION

Ultrasonic non-destructive testing (NDT) techniques are widely used to detect flaws or defects within structural and functional components, and to classify and characterize the defects by their size, shape, location, orientation etc. Techniques which have been used include: A-scan, B-scan and Synthetic Aperture Focusing Technique (SAFT). Of these, A-scan is difficult to interpret without extensive operator training, and may lead to unreliable inspections. B-scan is easy to interpret, but it also has some disadvantages, such as that forming a B-scan image with an unfocused transducer leads to poor lateral resolution, and if using a focused transducer, the dynamic focusing technique has to be used to obtain good lateral resolution in all the regions of interest . SAFT, on the other hand, can get an image with good lateral resolution in all the regions of interest. The basic principle of SAFT is to apply a signal processing algorithm to a collection of raw A-line data from different transducer positions. The algorithm allows each point within the inspected volume to be focused upon by mathematically simulating the action of a lens. This algorithm involves the summation of the raw RF data shifted by predicted time delay. SAFT has been used for the fine grained materials ultrasonic evaluation with excellent results [9] [10]. However, use of SAFT in coarse grained material results in an image which suffers from ultrasonic speckle. The presence of speckle reduces the detectability of targets. This problem is also encountered in ultrasonic A-scan and B-scan coarse grained material testing.

Speckle is actually an interference pattern due to the presence of grain noise in each raw A-line signal. The grain noise is produced by those unresolvable, randomly distributed scatterers within the range cell, as shown in Fig. 1. Echoes from these scatterers add randomly, and result in the grain noise signals in the A-scan signal, which in turn results in the speckled appearance in the SAFT image. Echo y (t) from a certain range of depth can be expressed as :

$$y(t) = \sum_{i=1}^{N} A_i \, x(t - \tau_i) \qquad (1)$$

where x(t) is the attenuated transmitted signal, N is the number of scatterers in the range cell. A_i is the back scattering coefficient of the i th scatterer. is the propagation time of the ultrasonic wave from the transducer to the i th scatterer. Grain noise amplitude y (t) is

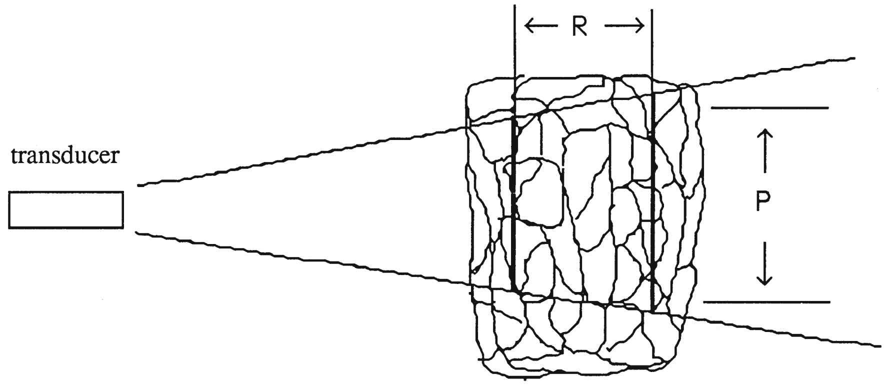

Fig. 1. Origin of grain noise in A-line signal. It is due to the random summation of many small echoes from the grain boundaries in the range cell. The range cell length R is equal to one half of the pulse length.

related to the range cell size. The two dimensional size of the range cell is determined by its length R along range direction, and the length P cross the sound beam.

Some methods have been developed to reduce grain noise or speckle in ultrasonic A-scan [1] [2] [4] [5] and B-scan images [7] [8], such as frequency diversity and spatial diversity. The frequency diversity method is based on the fact that speckled appearance is frequency dependent, because frequency change will alter the phase of each small echo in equation (1), resulting in the grain noise amplitude y(t) on the same depth range changing randomly. The spatial diversity method based on that speckled appearance is also spatial dependent, because when the transducer position is changed a bit, the distribution of scatterers in the range cell at the same depth range will be changed, resulting in the grain noise amplitude y(t) changing randomly. In contrast to speckle, it is assumed that any object of interest will exhibit little change in the processing range of the frequency and spatial diversity*. In these methods, first, frequency and / or position diversity has been introduced in such a manner that multiple uncorrelated speckled pattern are generated, but target signals have almost no change. Then these signals were processed with several algorithms, including averaging, minimization and polarity thresholding. Through these algorithms, the amplitude of the processed signal becomes small when only speckle is present and becomes large when a target is present, so signal-to-noise ratio is improved. Each algorithm can be expressed mathematically as the following(using the B-scan image as an example):

Averaging algorithm:

$$Y(n,m) = \text{mean}\ (X_i(n,m))$$

Minimization algorithm:

$$Y(n,m)=\min\ (| X_i(n,m) |)$$

Polarity threshold algorithm:

$$Y(n,m)=\begin{cases}\text{mean}(X_i(n,m)) & \text{if} \quad \text{all } X_i(n,m)>0 \text{ (or } <0) \quad i=1,2... N \\ = 0 & \text{if} \quad \text{other}\end{cases}$$

* If the target reflect coefficient is much bigger(say more than ten times) than that of scatterers, and the target is kept in the range cell when the transducer position is shifted, this assumption is correct.

where $X_i(n,m)$ is the i th sub-image get from frequency or spatial diversity, Y(n,m) is the processed image. N is the total number of sub-images.

SAFT image speckle reduction has been done in radar [11]. Frequency and spatial diversity * techniques have also been used to create uncorrelated sub-images. But only the incoherent averaging algorithm has been used to compound these sub-images. Because nonlinear algorithms have been shown to achieve better grain noise reduction than averaging in A-scan and B-scan ultrasonic NDT[5] [6], in this paper we will evaluate the effect of nonlinear algorithm on SAFT image SSP processing. We will also evaluate the effect of a so called interlaced array method combined with the SSP and nonlinear algorithm to reduce speckle in the ultrasonic SAFT image. This is a method which combines spatial diversity and frequency diversity.

It should be noticed that the SAFT algorithm itself has some effect on speckle reduction. In SAFT a transducer which has a very wide beam width is employed, so the range cell size in the cross dimension is very big. SAFT processing will reduce it to one half of the transducer diameter, and the speckle amplitude will be reduced compared with the original B-scan image formed from those original A-line signals. But for coarse grained materials, even in this range cell(after SAFT process), the speckle is still strong enough to interfere with the interpretation of the image, so further processing is necessary. In the next section, we will discuss the details of the work we did on ultrasonic SAFT imaging speckle reduction.

SAFT IMAGE SPECKLE REDUCTION

L. J. Porcello et al [11] have evaluated the ability of speckle reduction of the frequency diversity method in Radar SAFT image. In this method, a wide-band signal was sent out from each transducer position to get all the raw RF signals. After this, one splits the spectrum of each raw A-line to get several sets of A-line signals which have different frequency bands. Then one uses each sub-band A-line signal set to create a SAFT sub-image. The final processed image is made by incoherently averaging all these sub-images.

In this paper, we have used a different frequency diversity approach from the one used in radar. In this approach, one forms a SAFT image first from the wide-band raw A-line signals, then processes each column of this image by SSP combined with the nonlinear algorithm. The reason for doing this is that SAFT image is equivalent to a B-scan image obtained from a transducer which has a lateral resolution equal to one half of the transducer diameter in all the interested region, so split spectrum processing can be used on each column of this image with those nonlinear algorithms to reduce the speckle in it. The first advantage of this approach over the one used in radar is speed, because only one SAFT image instead of the many images is constructed in the processing. The second advantage is that the polarity thresholding algorithm has been shown [6] to do better speckle reduction than the incoherent averaging.

In the work of Porcello et al [11], angular diversity and frequency diversity have also been combined together to create more uncorrelated images. The angular diversity is introduced by using the Doppler technique to separate the wide beam of the transmitted signal into several small beams with different direction. Because the Doppler method can only be used when the aperture is sufficiently small [12], this method sacrifices the lateral resolution for the reduction of speckle.

We also use a different method, the so called interlaced array technique, to combine spatial diversity with frequency diversity to reduce SAFT image speckle. The geometry of this method is shown in Fig. 2. In this method, we first chose those A-lines which are separated by K A-lines to make a sub-SAFT image $Y_{i(n,m)}$, thus we create K SAFT sub-images. To reduce the speckle in these sub-images, we can use SSP with the nonlinear algorithms on each column of sub-image $Y_{i(n,m)}$ to get the image $Z_{i(n,m)}$. This will suppress most of the speckle in the image Yi(n,m). But there will be still some speckle remaining in

* Actually angular diversity was used in their work, it is equivalent to spatial diversity.

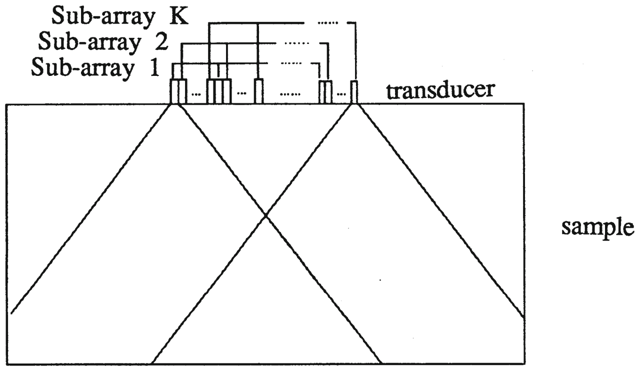

Fig. 2. Interlaced array.

$Z_i(n,m)$. This is because scatterers in a range cell are randomly distributed, so in some range cells, due to the special scatterer distribution in them, the echo amplitude is not very frequency sensitive, and SSP can not distinguish it from target signal. But for sub-images obtained from different sub-arrays, the range cell position in the same point of the image will have some change, so the distribution of scatterers in these range cells will be different, consequently, the signal may become sensitive to frequency change[2] [3]. When compounding these sub-images by using the polarity thresholding algorithm on each point of these images, speckle will be reduced again in the final processed image Z(n,m). Because we assume that target signals do not change significantly when frequency and sub-array are changed, the target signal will remain after going through this process.

The success of the interlaced array method requires two basic conditions: first, from each sub-array, a good quality conventional SAFT image should be able to be synthesized, and second, the speckle pattern in these sub-images should be sufficiently uncorrelated. These conditions are satisfied by the following facts: According to the SAFT theory [9], the optimal transducer position shift (spatial sampling rate) in the aperture for forming a SAFT image is equal to one half of the transducer diameter(lateral resolution); and it was also found in ultrasonic NDE [2] [3] that the grain noise pattern in an A-line signal is significantly changed when the transducer position is shifted much less than the one half transducer diameter. So we can use the interlaced array method as we described before to reduce the speckle in SAFT images.

In the interlaced array method, the equivalent aperture of each sub-aperture is nearly equal to the total aperture, so there is no sacrifice of lateral resolution in this method. Another thing that should be mentioned here is that these sub-arrays treat all the inspected region evenly, so there is no need to normalize the beam intensity directivity.

The interlaced array method can be expressed mathematically as three steps:

Step 1: Form K sub-images $Y_i(n,m)$ with sub-array T_{ij}:

$$Y_i(n,m) = \mathrm{SAFT}(T_{ij}) \qquad i=1,2\ldots\ldots K$$

where T_{ij} is the j th A-line in the i th sub-array.

Step 2: Split spectrum process Yi(n,m) with polarity thresholding algorithm to obtain K processed sub-images Zi(n,m):

$$Z_i(n,m) = \mathrm{SSP}(Y_i(n,m)) \qquad i=1,2\ldots\ldots K$$

this step is the frequency diversity processing.

Step 3: Process these $Z_{i(n,m)}$ with Polarity Thresholding (PT) on each point (n, m) of the image to get the final processed image Z(n,m):

$$Z(n,m) = PT (Z_{i(n,m)})$$

this step is the spatial diversity processing.

Actually, in the experiment, we switched step 2 with step 3. The overall effect is nearly the same; however, in this case the split spectrum process is needed only once, rather than K times.

EXPERIMENTAL RESULTS

We chose an equiaxed grain Centrifugally Cast Stainless Steel (CCSS) block as our experimental sample which is shown in Fig. 3. Its grain size is large, so the SAFT image has a speckled appearance. Ultrasonic wave velocity in this sample is 5800 m/s. The hole in it simulates a target. The hole diameter is 3.18 mm (0.125 in.). The experimental system is shown in Fig. 4. We use an unfocused transducer with a nominal center frequency of 2.25 MHz and band-width of 1.25 MHz. In this frequency region, most of the energy can propagate to the bottom of the sample without too much attenuation. The diameter of the transducer is 12.7 mm (0.5 in.), the resolution of SAFT image should be 6.4 mm (0.25 in.).

The scanning of the transducer is controlled by a scanner, which is in turn controlled by PDP-11/23. The transducer scans in the region as shown in Fig. 3. The aperture length is 27.9 mm(1.1 in.). We take 256 total transducer positions in this region. From each transducer position we get one A-line signal, and from the 256 A-line signals a synthetic aperture image can be synthesized.

The A/D convertor is used at 20 MHz sample rate, and 8 bits magnitude resolution. Signal storage length is 256 Points, that is 12.8 ms total signal time length, corresponding to 37.1 mm depth range in the sample. All of these signals are put into the PDP-11/23 and manipulated in it. The processed image is demonstrated by the plotter.

B-scan image formed from the 256 raw A-line signals is shown in Fig. 5 (the two lines are due to the positive and negative peaks of the transmitted signal). The noise in the image is strong due to the large grain size and the large range cell . The target is extended due to the wide beam width.

Next, we apply conventional Synthetic Aperture Focusing Technique to these raw A-lines. The resulting SAFT image is shown in Fig. 6. The lateral resolution becomes better, but not very much. This is because the diameter of the transducer used in this experiment is big. In the future work, we will use a transducer which has smaller diameter to achieve better lateral resolution. Grain noise in the image has also been reduced because the lateral resolution becomes better, but there is still considerable noise remaining in the image.

Then we use SSP technique with the polarity thresholding algorithm on each column of Fig. 6 to reduce the speckle. The result is shown in Fig. 7. The grain noises have been reduced. We can also see from the image that there is still some noise remaining. The reason for this is that the distribution of scatterer centers in the range cell is random. It is possible that in some places the grain noise may not be sensitive to frequency change in the processing frequency range[5]. If it can not be eliminated by using frequency processing alone, we must combine it with the spatial processing.

Finally, we use the interlaced array technique on those raw A-line signals. In this method, we first choose those A-lines which are separated by 32 A-lines to make 32 SAFT sub-images. Then we apply the polarity thresholding algorithm on each point of these sub-images. the processed image is shown in Fig. 8. The lateral resolution is better and the grain noise is reduced in this image. Then we use SSP combined with polarity thresholding to process each row of the image. The final processed image is shown in Fig. 9. The grain noise has been further reduced.

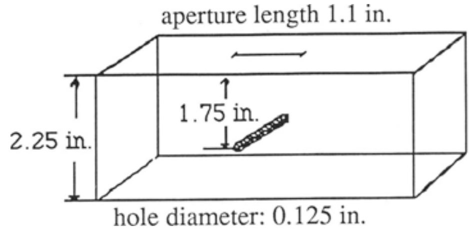

Fig. 3. Equiaxed grains centrifugally cast stainless steel sample.

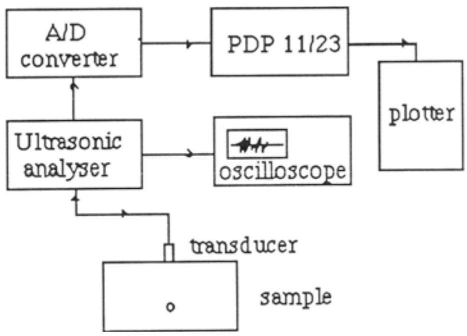

Fig. 4. Experimental system

SUMMARY

Because the SAFT image has very good lateral resolution in all the regions of interest, it has been introduced into ultrasonic NDT on fine grained materials. In this work, ultrasonic SAFT technique has been used on coarse grained materials*, and it is found that there is much speckle in the image, which makes the image difficult to interpret.

In this work, the SSP technique combined with polarity thresholding algorithm has been used on the SAFT image to reduce speckle in it. Experimental results have shown very good effect. It should be noticed that although the use of nonlinear algorithm in the split spectrum processing can achieve better SNR improvement, the chance of losing a target becomes higher than tin the averaging algorithm, especially when multiple targets appear in the same range cell.

In this work, a so called interlaced array method has also been used to reduce the speckle in the SAFT image,which is made possible by the fact that the optimal transducer position shift in the aperture for forming a SAFT image is around one half of the transducer diameter (lateral resolution), and the shift of transducer position necessary to obtain significant noise pattern change in the A-line is much less than that. Experiment results show that the speckle appearance in the image was dramatically reduced by this method.

Further study is needed on how the choice of the processing parameters, such as the transducer position shift in each sub-array and the transducer position shift between sub-arrays, will influence the effect of the interlaced array method on speckle reduction. We also intend to do some work on the SAFT imaging technique, which uses a two dimensional transducer array, and the speckle reduction techniques for this kind of SAFT image.

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* Because SAFT requires accurate phase information, and wave propagation in coarse grained material tend to be unpredictable, so there are some disadvantage of SAFT on coarse grain image imaging, but it is still usable in certain areas.

Fig.5. B-scan image made by the 256 raw A-scan signals. The grain noise is srtong and the target is extended.

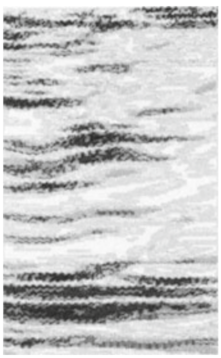

Fig.6. SAFT image synthesized from the 256 raw A-scan signals. The lateral resolution becomes better.

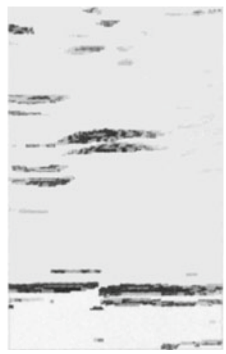

Fig.7: Processed image made by applying SSP with the polarity threshold algorithm on each column of the image in Fig. 6. Grain noises have been reduced.

Fig.8. Processed image made by applying the polarity thresholding algorithm on each point of 32 sub-images obtained from 32 sub-arrays.The lateral resolution is better and the grain noise is reduced

Fig.9: The final processed image of interlaced array method obtained by applying SSP with polarity thresholding algorithm on each column of the image in Fig. 8.The grain noise has been further reduced.

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